Electric Drives Experiment 5
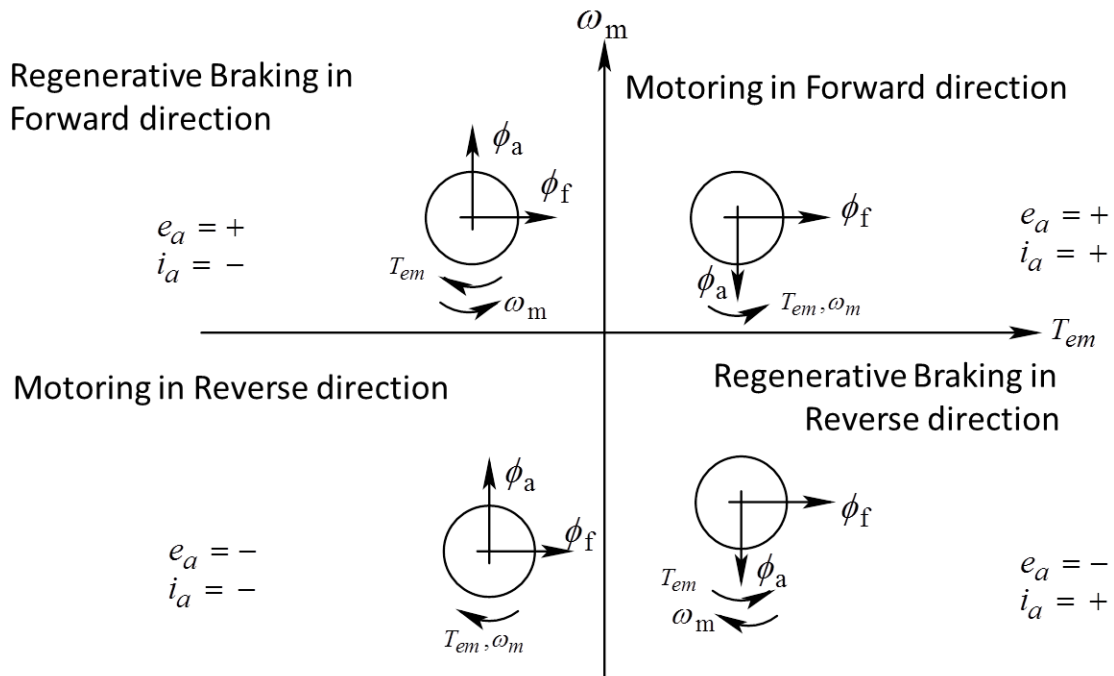
Four-Quadrant Operation of a PMDC Motor

5.1 Objective

The objective of this activity is to analyze the four-quadrant operation of a permanent-magnet DC (PMDC) motor. This activity was derived from those developed and distributed by the University of Minnesota (UMN).

5.2 Review of Four-Quadrant Operation

As demonstrated in Figure 5.1, a motor will consume power when the electromagnetic torque it produces is in the same direction as the motor's rotation, or similarly, when the polarity of the voltage across the armature coil is in the same direction as the current flowing through the coil. This situation applies in quadrants 1 and 3 shown in the figure. However, in cases where the torque and rotation are in opposite directions (and where the current flows opposite to the voltage polarity across the armature coil), the motor will serve as a generator and will produce power. This situation is represented by quadrants 2 and 4 in Figure 5.1. In this lab, you will operate the lab's PMDC motor in all four of these modes.

Figure 5.1: Diagram representing four-quadrant motor operation (UMN, Mohan).

5.3 Analyzing Four-Quadrant Operation of a PMDC Motor

Download the "Exp5.mdl" MATLAB Simulink model from the location specified by your TA or instructor. Rename the file to remove any parentheses added during the download process. Open the model in the 32-bit version of MATLAB Simulink. In the model, double-click on the Wm_Reference module, and change the time values to the following array:
    [0 2 2.3 4 4.3 6 6.3 8 8.3 10]

Change the output values (the desired motor speed in radians/sec) associated with these times to:
    [0 0 100 100 0 0 -100 -100 0 0]

Only one space is needed between each number. Note that these entries will cause the motor to linearly ramp up from 0 to 100 radians/second in 0.3 seconds (between times 2.0 and 2.3 seconds). Similarly, it will fall from 100 to 0 rad/s in 0.3 seconds (from 4.0 to 4.3 seconds), fall from 0 to -100 rad/s in 0.3 seconds (between 6.0 to 6.3 seconds), and so on.

In Simulink, add the ability to access the motor's armature voltage via the CP1104's eighth ADC port by first copying and pasting the dSPACE module labeled _DS1104ADC_C5, then double-clicking on the new module and changing the channel number to 8. (Select OK.) As shown in Figure 5.2, use a gain block to multiply the DS1104 value by 10, to convert from the sensed value to the actual voltage. Rename the gain block to "Va_Measured". Next, use a "Product" module from Simulink's "Commonly Used Blocks" library and connect the measured armature voltage and current values (Va_Measured and Ia_Measured) to the product module. Rename the product module to "P_elec", indicating that this product represents the electric power input to the PMDC motor. Connect a "Terminator" module to the output of the "P_elec" module.

You will next add a measurement of the motor's mechanical power, $P_{mech} = T_{em} \, \omega_m$. To begin, copy and paste the "P_elec" module (with Terminator) and rename it to "P_mech". Connect the "Wm_Reference" variable to one of the module's input ports (we're using the reference rather than the measured speed value because the measurement is noisy and the result will still be accurate, given the use of a speed controller). Knowing that $T_{em} = k_T \, I_a$, and using a value of k_T that you used in previous labs, connect the "Ia_Measured" variable multiplied by k_T to the remaining "P_mech" input port, as shown in Figure 5.2. Also create an output module for T_{em}. Compare your model against Figure 5.2, and save your model.

Type Ctrl-B to create the executable for your MATLAB Simulink model, and check that the resulting executable loads successfully onto the DS1104 board. Connect the lab hardware as you have done for the past few experiments, being careful not to supply any of the three sources of power to the inverter board until your setup is complete. (The three sources of power include the 40 V DC input, the analog power associated with the toggle switch, and the digital power supplied by the CP1104 board.) In addition, connect a cable with a BNC connector on one end and either banana connectors or alligator clips on the other end (found on the outside of the electric drives cabinet) between the CP1104's ADC port #8 and the drive motor's voltage, as shown in Figure 5.3. If you use alligator clips, connect the red and black clips to the metal inside the power electronic board's Phase A1 and B1 ports, respectively, as it is difficult to get a good connection between these clips and the motor's ports directly. If you use the banana leads, connect the port labeled GND to the motor's red connector, and connect the other port to the motor's black connector, as shown in Figure 5.3.
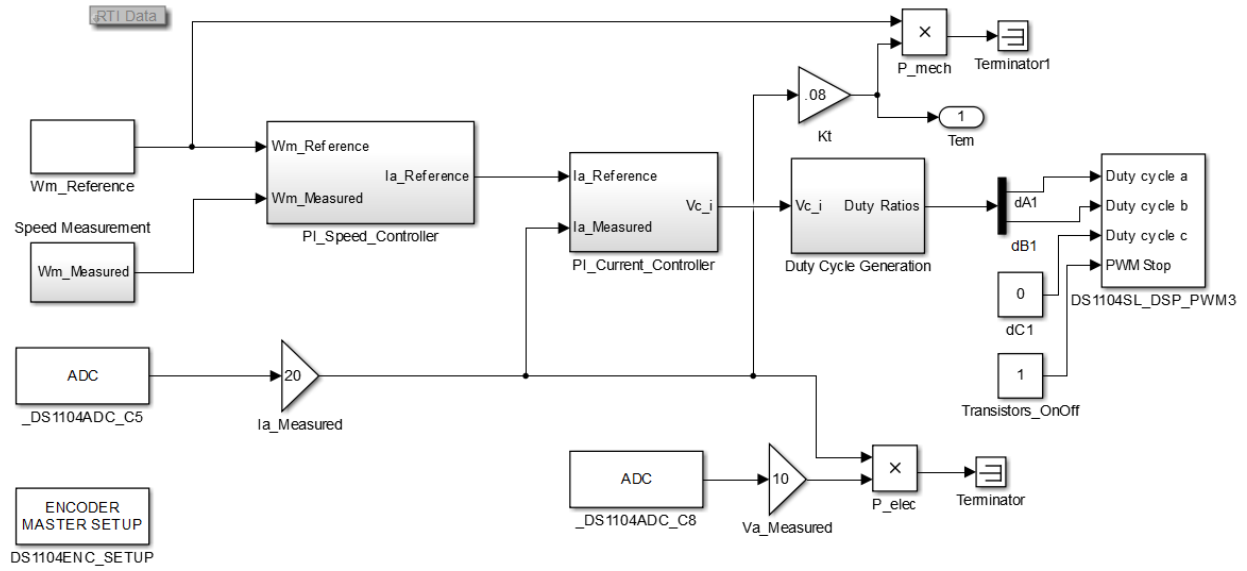
**Figure 5.2:** MATLAB Simulink file associated with Section 5.3.

(a)

(b)
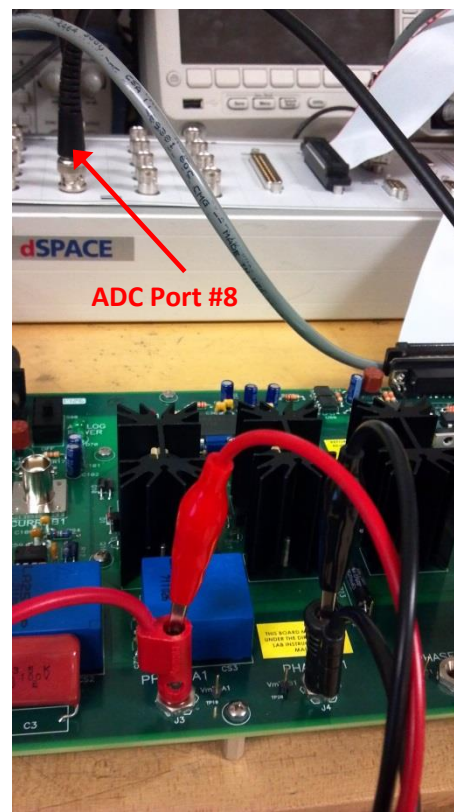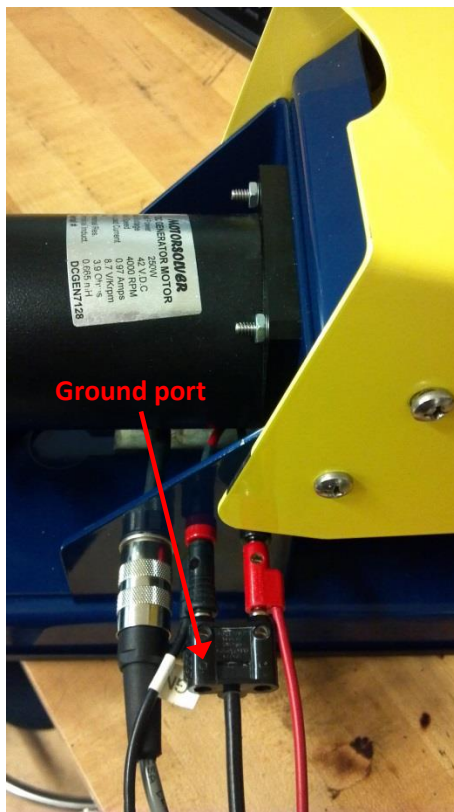
Figure 5.3: Connecting the motor's armature voltage to the CP1104 board's ADC port #8 using a cable with a BNC connector on one end and (a) banana or (b) alligator clips on the other end.

Start ControlDesk, create a new Project + Experiment, and load the variable definition file that you just created in MATLAB. Create a checkbox for the "Transistors_OnOff" variable, and in its Instrument Properties window, change the "On-Value" to 0 and the "Off-value" to 1. Next, create a plotter that will show "Va_Measured" and "Ia_Measured" on the same graph but with different y-axis scales: To do this, drag **each** of these variables onto the graphing section of the plotter, rather than onto the y-axis, to create different axis scales for these variables. You may have to resize the window sections to see both y-axes clearly. Create a second plotter for "Wm_Measured" (found under PI_Speed_Controller) and "Tem", again with different y-axes for the two variables. Create a third plotter to display "P_elec" and "P_mech" using the same y-axis (to do this, drag the second variable onto the y-axis rather than the graphing window). Set the time duration for the plots to 20 seconds (hint: Measurement Configuration window, Duration Triggers…). Save your ControlDesk project / experiment.

Select the "Start Measuring" icon in ControlDesk. Turn on the toggle switch associated with the analog power supply for the power electronics board, and turn on the 40 V power supply. Check the "Transistors_OnOff" checkbox in ControlDesk to supply power to the motor. If the red "Motor Fault" LED lights up and the motor does not spin, press the "Reset" button in the upper-right corner of the inverter board for a few seconds. Ask the TA or instructor for assistance if the motor still does not spin.

The plot of "Va_Measured" will be very noisy, showing the on-off switching of the PWM waveform. Press "Stop Measuring" and *save an image which shows at least 10 seconds of the voltage waveform*. Then zoom in until you see just a few PWM cycles at a time when the average voltage is positive. Hint: Look for a portion of the graph where the current is positive, then zoom in so that you still see the full range of +/- 10 V while looking at shorter segments in time. The result should look similar to Figure 5.4 *Save a copy of the zoomed view*. *Estimate the duty ratio of the PWM signal from the zoomed graph.* (Recall that $d = T_{up} / T_s$, where T_{up} is the time in one period that the transistors are conducting and T_s is the switching period. Using the plotter's cursor utility may help you get a more accurate value.) *Show your work.*
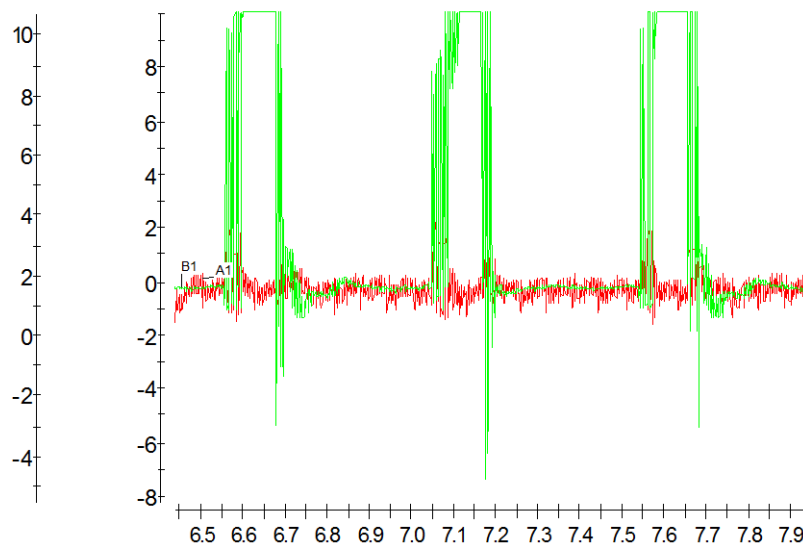
Figure 5.4: Zoom of PWM armature voltage waveform when the average voltage and current are positive.

Use the lab bench multimeter to measure the RMS DC voltage across the motor's armature coil as the motor goes through the cycle of desired speeds – there should be different average voltages for the speeds of +100, 0, and -100 radians/second. *Record your observed RMS armature voltages and the associated speeds.* Given that the power electronic board's input DC voltage is 40 V, and $V_a = d\ V_{in}$ *does your estimate for the duty ratio match with the measured positive RMS armature voltage? Explain your answer.* (Note that the DS1104 ADC converters cannot read higher than 10 V, so the peak values of your PWM voltage waveform should be 40 V but are clipped to 10 V in the ControlDesk plotter.)

Uncheck the "Transistors_OnOff" checkbox to turn off the transistors, and turn off the 40 V power supply. Move the connectors associated with armature voltage measurement – which provide a signal to the CP1104 board's ADC port #8 – so that they connect to the load motor on the MotorSolver kit rather than the drive motor, as shown in Figure 5.5. Note that the ground lead will be connected to the motor's black port in this case. Do **not** connect the load motor to the Phase A1 and Phase B1 voltages – you are only moving the sensor location for the ADC port #8. Since the drive and load motors are identical, this change is associated with measuring the motor's EMF rather than its armature voltage. The EMF waveform is much smoother than the PWM armature voltage and will still provide accurate values for the power being applied to the motor's load.
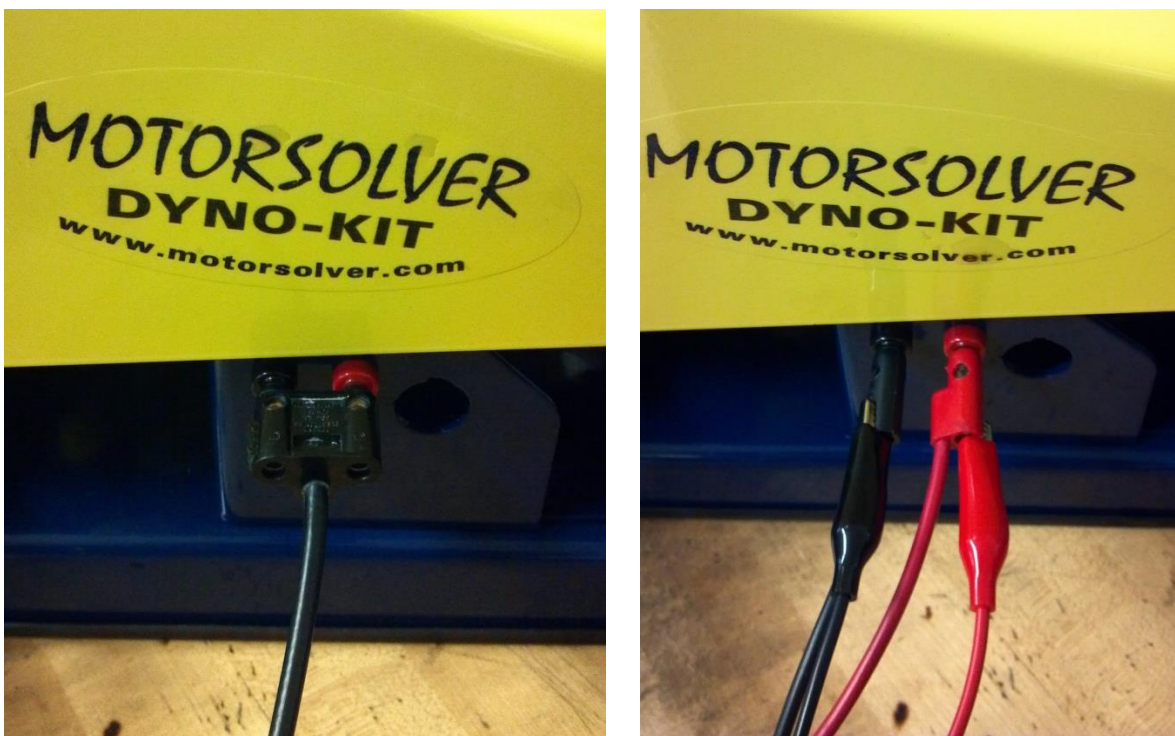
Figure 5.5: Connecting the load DC motor to the CP1104 board's ADC port #8.

Press the "Start Measuring" icon in ControlDesk, turn on the power electronic board's 40 V power supply, and check the "Transistors_OnOff" checkbox. Your voltage (EMF) waveform should be much smoother. If the waveform looks flat (zero) rather than square, double-check that you are connecting to the metal within the load motor's ports, rather than plastic.

Save images of the three plotters' graphs which show data for a full cycle of the desired speed waveform. Analyze these plots in your lab report. For example, indicate sections of an example plot where the motor is operating in each of the quadrant 1, 2, 3, and 4 modes. (Hint: When torque is negative and speed is positive, as is the case in generating quadrant 2, what will be the sign of the output power?)

Zoom into the plot of P_{elec} and P_{mech} when the motor is in a regenerating mode. *Save a copy of this image. Estimate the maximum (negative, averaging the noisy spikes) mechanical power in the chosen regenerating mode. Use the mechanical data to estimate the energy regenerated by the motor during the regeneration period, showing your work* (for example, the integration of the output power curve during the time when the power is negative may be approximately ½ *base* x *height* if the area is similar to a triangle). *How does this regenerated energy compare to the motor's kinetic energy before it was turned off,* $KE = \frac{1}{2} J_{eq} \omega_m^2$? (Use J_{eq} = 5 x 10^{-4} kg-m^2 as an estimate.) Turn off the toggle switch that provides analog power to the power electronics board, and turn off the 40 V power supply. Close the ControlDesk software, saving any changes.

5.4 Analyzing the Effects of Ramp Time and Speed on Regenerated Power and Energy

Return to the MATLAB Simulink file that you created in Section 5.3, and change the time duration of each ramp in speed from 0.3 to 0.15 seconds. (Open the "Wm_Reference" module, and change each instance of .3 in the time series to .15.) *How do you think this faster ramp will affect the instantaneous power and total energy regenerated by the motor during quadrant 2 or quadrant 4 operation?* To test your answer, create an executable of your modified Simulink file (Ctrl-B), start ControlDesk, and open the project + experiment that you modified earlier in this lab. Press the "Start Measuring" button in ControlDesk, answering "Yes" to loading your revised variable description file. Ensure that the "Transistors_OnOff" box is checked, and turn on the power electronic board's analog and 40 V power supplies. *Save a zoomed image of a regeneration period. Estimate the maximum (negative) mechanical power in the chosen regenerating mode. Estimate the mechanical energy regenerated by the motor during the regeneration period, showing your work. How do these values compare to the previous case, when the ramp period was twice its present value? How does this compare to your expectations?*

Uncheck the Transistors_OnOff box, turn off the toggle switch that provides analog power to the power electronics board, and turn off the 40 V power supply. Close the ControlDesk software.

Back in MATLAB, change all of the desired speed's time ramps back to 0.3 seconds, and change the desired speeds that were +100 to +150 radians/second. Also change the -100 values to -150. Make an executable of the new Simulink model, and open ControlDesk using the same project and experiment that you used earlier. Press the "Start Measuring" button in ControlDesk, ensure

that the "Transistors_OnOff" box is checked, and turn on the power electronic board's analog and 40 V power supplies. *Save a zoomed image of a regeneration period. Estimate the maximum (negative) mechanical power in the chosen regenerating mode. Estimate the mechanical energy regenerated by the motor during the regeneration period, showing your work. How do these values compare to the original case, when the initial speed and therefore kinetic energy were lower but the regeneration time was the same? Explain.*

Turn off the 40 V power supply and the toggle switch for the analog power. Shut down the ControlDesk and MATLAB software programs.

5.5 Shutdown Procedures

Remember to turn off and remove the three power sources first to reduce the probability of damaging the board.

- **Turn off the high-power DC power supply first, without reducing its output voltage.**

- Turn off the toggle switch associated with +/- 12V power supply, and unplug this power supply.

- Remove the ribbon cable from the inverter board and the CP1104 board.

- Remove the black cable from the DS1104 PC board (at the back of the lab computer).

- Remove the BNC-BNC and encoder cables.

- Remove all banana cables and store them at the lab benches as usual.

- Replace the inverter board inside the protective electrostatic cover.

- Carefully return all of the specialized electric drives components to a table near the lab's cabinet. The TA or the instructor will place the equipment back into the cabinet.

- Check that all of the test bench equipment is turned off, and leave the test bench area clean and organized. Your lab grade will be lowered if you are not careful with the lab equipment and/or if you leave trash in the test bench area.

5.6 Lab Report

The group of students at each lab station should submit a lab report. The report should focus on presenting and analyzing the data collected in this lab, although your instructor or TA may provide additional questions or requirements for your report. The requested data were often emphasized in the procedures with italicized text. The report should have section headings to help organize your information. Each figure should have a label and a brief description placed below the image, as demonstrated in these procedures, and each figure should be referenced in the text. Your analysis should be written in prose (i.e., complete sentences); the report should not just contain a collection of images and numbers. Think about writing the report such that you can use it later in the semester as a study guide. Show the equations or processes used to calculate

values that were not directly measured. Your instructor or TA will announce the due date and method for submitting your report.

Checklist of items requested in these lab procedures:

☐ Save two images showing the PMDC motor's PWM-generated armature voltage – one image showing the waveform for at least 10 seconds and the other image showing a zoomed view of a few PWM cycles.

☐ Estimate the duty ratio of the PWM signal from the zoomed graph. Show your work.

☐ Use the lab bench's multimeter to measure the RMS DC voltage across the motor's armature coil as the motor goes through the cycle of desired speeds. Record your observed RMS armature voltages and the associated speeds. Given that the power electronic board's input DC voltage is 40 V, does your estimate for the duty ratio match with the measured RMS armature voltage? Explain your answer.

☐ Save images showing the PMDC motor's (1) induced EMF and current, (2) torque and speed, and (3) electrical and mechanical power when a cascaded control system is in place and the speed is varied between 0, 100, and -100 radians/second.

☐ Analyze the three images described in the previous bullet. For example, indicate sections of an example plot where the motor is operating in quadrant 1, 2, 3, and 4 modes.

☐ Zoom into the plot of P_{elec} and P_{mech} when the motor is in a regenerating mode. Save a copy of this image.

☐ Record the maximum mechanical power in the chosen regenerating mode.

☐ Estimate the energy regenerated by the motor during the regeneration period, showing your work.

☐ How does this regenerated energy compare to the motor's kinetic energy before it was turned off, $KE = \dfrac{1}{2} J_{eq} \omega_m^2$?

☐ How did you expect the faster ramp to affect the power regenerated by the controlled PMDC motor during quadrant 2 or quadrant 4 operation?

☐ For the case when the ramp was changed from 0.3 to 0.15 seconds: Save a zoomed image of a regeneration period. Estimate the maximum (negative) mechanical power and calculate the mechanical energy regenerated during the regeneration period, showing your work. How do these values compare to the previous case, when the ramp period was twice its present value? How does this compare to your expectations? Explain.

☐ For the case when the speed's magnitude was changed from 100 to 150 radians per second: Save a zoomed image of a regeneration period. Estimate the maximum negative mechanical power and the mechanical energy regenerated during the regeneration period. How do these values compare to the original case, when the initial speed and therefore kinetic energy were smaller but the regeneration time was the same? Explain.